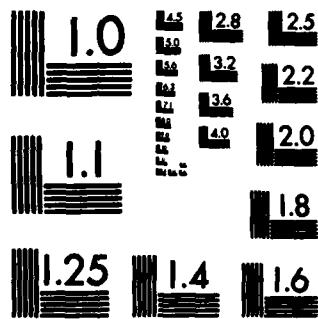


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indicating that most of the aluminum crystallites are oriented with a principal axis parallel to Z. Thermal annealing of the sample results in a small increase in ultrasonic velocity in all directions with the observed acoustic anisotropy remaining essentially unchanged.

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TECHNICAL REPORT No. 12

Measurement of Small Elastic Anisotropy in Solids
Using Laser Induced Ultrasonic Pulse

by

A. C. Tam

IBM Research Laboratory
San Jose, California

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**MEASUREMENT OF SMALL ELASTIC ANISOTROPY IN SOLIDS
USING LASER INDUCED ULTRASONIC PULSES**

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ABSTRACT: Nondestructive laser induced short ultrasonic pulse generation (duration ≈ 10 nsec) together with broadband detection are used to detect and measure the small elastic anisotropy in opaque solids quickly and precisely. This is demonstrated for extruded aluminum alloy type 6061-T6. A single laser-induced acoustic pulse propagation measurement over a path length of 47 mm provides a longitudinal ultrasonic velocity measurement accuracy of 0.02%. The longitudinal velocities at $\pm 45^\circ$ from the extruding direction Z are found to be 2% larger than the velocity along Z, indicating that most of the aluminum crystallites are oriented with a principal axis parallel to Z. Thermal annealing of the sample results in a small increase in ultrasonic velocity in all directions with the observed acoustic anisotropy remaining essentially unchanged.

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Ultrasonic wave velocity measurements have been widely used in many areas of material characterization such as measuring of the principle elastic moduli¹⁻³ and in nondestructive evaluations such as stress detection.⁴ In most of the experiments, the ultrasonic waves are generated by either piezoelectric, piezomagnetic, or electromagnetic acoustic transducers (EMAT). These transducers in general have limited bandwidths and are difficult to operate at high frequencies. Except EMAT, all other transducers must be in good contact with the specimen under investigation. Although EMAT allows noncontact measurement, it has the disadvantage of low sensitivity and is limited to electrically conductive samples only. The use of laser pulses to generate ultrasonic waves (opto-acoustic effect) in opaque solids⁵⁻¹³ provides an alternative way of generating ultrasonic waves without contacting the sample. Furthermore, extremely short ultrasonic pulses can be created.¹³ This is especially useful when accurate timing is needed such as in the determination of ultrasonic velocity, and in broadband ultrasonic absorption measurement where broad Fourier frequency is necessary.^{14,15} In this letter, we report an experiment using laser generated short ultrasonic pulses to study the elastic anisotropy of extruded aluminum bar. We demonstrated that elastic modulus can be determined to an accuracy of 0.04% (equivalent to 0.02% accuracy in ultrasonic velocity) in aluminum with one single pulsed measurement (which takes approximately 10 μ s). Conventional technique such as sing-around method^{16,17} and pulse-overlapping method¹⁸ can achieve this precision at the expense of much longer measuring time (of the order of seconds) because of the "time-average" nature of these methods.

Our experimental setup is shown in Fig. 1. A nitrogen laser beam of wavelength 337 nm and pulse duration 8 ns is used as the excitation source. To avoid damage of the

sample, the energy of each pulse is limited to 1 mJ or less, and the laser beam is gently focussed to a size of approximately 4 mm^2 at the surface of the sample. The sample materials used in this experiment are commercial extruded bars of aluminum alloy (CACO aluminum type 6061-T6 QQA 200/8) of width 76 mm, and thickness 4.76 mm or 9.60 mm. The samples presently used are in the form of discs of diameter 46.97 mm cut from the central part of the extruded bars with the flat surfaces of the bars not scratched. Extra care is used in cutting out the samples so that the sample temperature is always below 100°C during cutting.

In order to achieve high temporal resolution and to detect the short ultrasonic pulse ($\sim 10 \text{ ns}$) generated by the laser beam in the sample, a broadband receiving transducer with short rise-time must be used. Suitably mounted PVF_2 piezoelectric transducer can have a bandwidth of tens of megahertz and a rise time of less than 10 ns.^{13,19} We use a 2 mm diameter, 52 μm thick poled PVF_2 film (Pennwalt Kynar No. 5412-144A-2) mounted in a modified BNC connector as the receiving transducers. A very thin water film is used to eliminate any trapped air between the transducer and the sample. The transducer and the laser spot are always arranged diametrically opposite at the sample so that the ultrasonic path length is equal to the diameter for all angular orientation of the sample. A low input-capacitance and high input-impedance FET buffer amplifier (Comlinear CLC-B-600) located very close to the transducer provides the desired impedance matching to couple the signal from the PVF_2 transducer to a fast preamplifier of 500 MHz bandwidth (Advantek AWL-500). The signal is displayed on a Tektronix 7854 oscilloscope equipped with a 7A24 vertical plug-in and 7B85 horizontal plug-in, and is finally recorded with Polaroid films. The arrival time of the ultrasonic pulse across the diameter of the sample is deduced from the position of

the signal on the oscilloscope screen together with the delay time of the horizontal sweep triggered by the signal from the photodiode. Typical traces of the ultrasonic pulse for several orientation angle θ between the extrusion axis and the acoustic propagation direction are shown in Fig. 2. The reproducibility of the arrival time measurement is observed to be ± 1 nsec. The diameter of the aluminum sample is 46.970 ± 0.005 mm. Hence the precision of our ultrasonic velocity measurement is approximately 0.02%.

Figure 3 shows the measured ultrasonic velocity $V(\theta)$ as a function of the angle θ for a disc sample. The result indicates the following: in the extruded aluminum alloy, the ultrasonic velocity $V(\theta)$ has a minimum in the extruding direction Z and a maximum at approximately 45° from Z. Define the anisotropy $A(\theta)$ in ultrasonic velocity at angle θ to be $A(\theta)=(V(\theta)-V(0^\circ))/V(0^\circ)$. Figure 3 shows that for the 6061-T6 sample of 4.76 mm thickness, $A(45^\circ)=0.0180$ and $A(90^\circ)=0.0049$. For another 6061-T6 sample of thickness 9.60 mm, we similarly measured $A(45^\circ)=0.0217$ and $A(90^\circ)=0.0050$. These results are very unusual. In most uniaxially oriented, rolled or extruded materials, the ultrasonic velocity is largest when the propagation direction is along the axis of working (rolling, extruding, etc.) and in most cases decreases monotonically to a minimum at 90° to the axis of symmetry.^{3,20-22} In order to explain the data of Fig. 3, we have computed the elastic anisotropy in aluminum (due to extrusion) using a "single phase aggregate" model.²³ In this model, the sample is assumed to be composed of very small identical aluminum crystallites each with intrinsic elastic moduli $C_{11}=108$ GPa, $C_{12}=61.3$ GPa and $C_{44}=28.5$ GPa, and density $\rho=2.70$, identical to those of a single crystal aluminum.^{24,25} The process of extruding is to produce a preferential distribution in the orientation of these units. For a given distribution, one can obtain

the bulk moduli of the sample by taking the ensemble average of the intrinsic moduli C_{ij} of the crystallites (Voigt average²⁶), or, one can apply the averaging process to the compliance constants S_{ij} of the crystallites to obtain the compliance of the bulk material (Reuss average²⁷). For materials with small anisotropy (as in our case), both Voigt average and Reuss average yield approximately the same result and therefore we shall proceed with the Voigt average in our analysis.

To obtain the distribution of the orientation of the aluminum crystallites, one can use the method of X-ray diffraction.^{3,22,28} However a simpler scheme — pseudo-affine deformation scheme^{29,30} is used here to model the orientation of the crystallites. In this scheme, the rotation of the symmetry axis of the aluminum crystallites is assumed to be the same as the rotation of lines joining material points in the sample. The dashed line in Fig. 3 shows the prediction of this model using a deformation ratio λ (defined as the ratio of the cross sectional area of the sample before extruding to the cross sectional area after extruding)=5, the only adjustable parameter in this model. This fairly large value of λ suggests (in the pseudo-affine deformation theory^{29,30}) that most of the crystallites have one of their three identical principal axis aligned along the extruding direction. This is possible because as pointed out by Musgrave,¹ aggregates of face-centered cubic crystals (such as aluminum) are very susceptible to elastic anisotropy by working. The agreement shown in Fig. 3 between the model and our measurement is exceptionally good and the most important feature, namely, $V(45^\circ) > V(90^\circ) > V(0^\circ)$ are predicted. Similar behavior has also been observed by other authors in shear wave velocity measurements^{4,21} in aluminum and Young's modulus measurements²⁰ in copper (also of cubic symmetry). However, the results presented here

seems to be the only detailed longitudinal (or quasi-longitudinal) wave measurement in aluminum which demonstrates this special feature.

According to the two-phase aggregate model,^{3,22,31,32} addition of small percentage of impurities in aluminum (such as those present in aluminum alloy 6061-T6) does not appreciably modify the bulk elastic properties (at small strain) of the material. This is supported by our data that the average ultrasonic velocity of the aluminum alloy 6061-T6 is approximately equal to that of pure aluminum.

Annealing the sample by heating it at 420°C for 4 hours and subsequently cooling to room temperature at a rate of 0.5°C/min raises all velocities by about 0.5%, but does not change the shape of the curve of velocity *versus* angle θ (see Fig. 3). The result indicates that the orientation of the crystallites remains essentially unchanged and the effect of annealing is to make the crystallites more perfect so that the ultrasonic velocity increases slightly. This finding is also supported by the work of Papadakis.²¹

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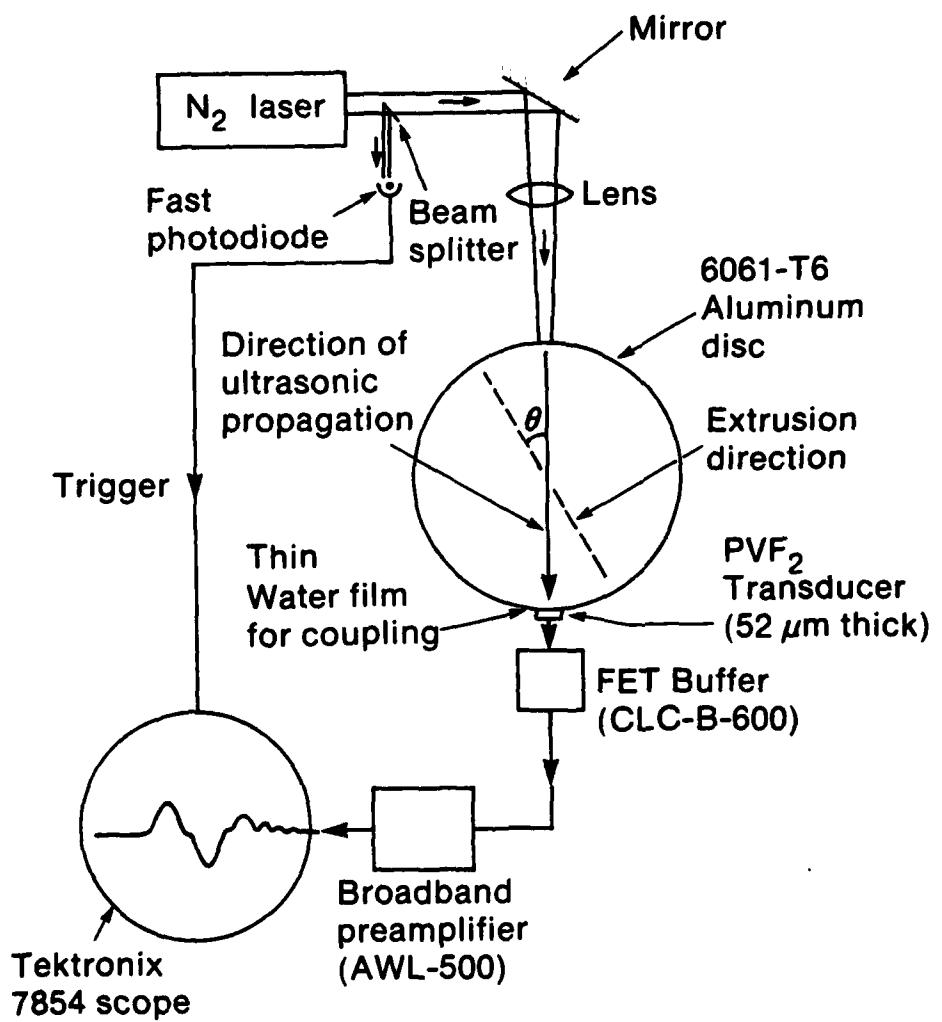


Figure 1. Schematic diagram of the experimental set up. θ is the angle between the direction of extrusion and that of ultrasonic wave propagation.

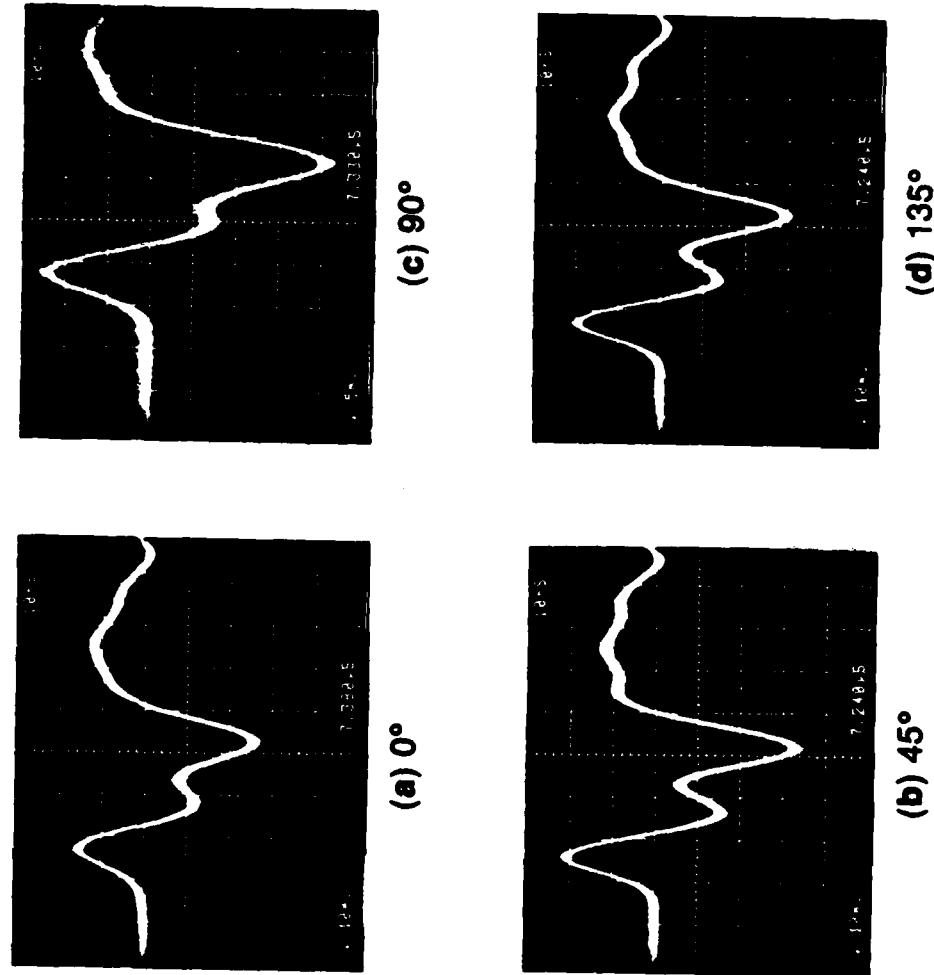


Figure 2. Ultrasonic signal as observed on the Tektronix 7854 oscilloscope for various values of θ , as indicated. The sample disc was cut from an aluminum 6061-T6 extruded bar of width 76 mm and thickness 4.76 mm. Horizontal scale is 10 nsec/div. The delay time in the horizontal sweep is 7.380 μ sec for (a), 7.240 μ sec for (b), 7.330 μ sec for (c), and 7.240 μ sec for (d). The negative-going peak, delayed by 26 nsec from the first positive-going peak in each photo is due to the transit time across the PVF₂ foil of thickness 52 μ m.

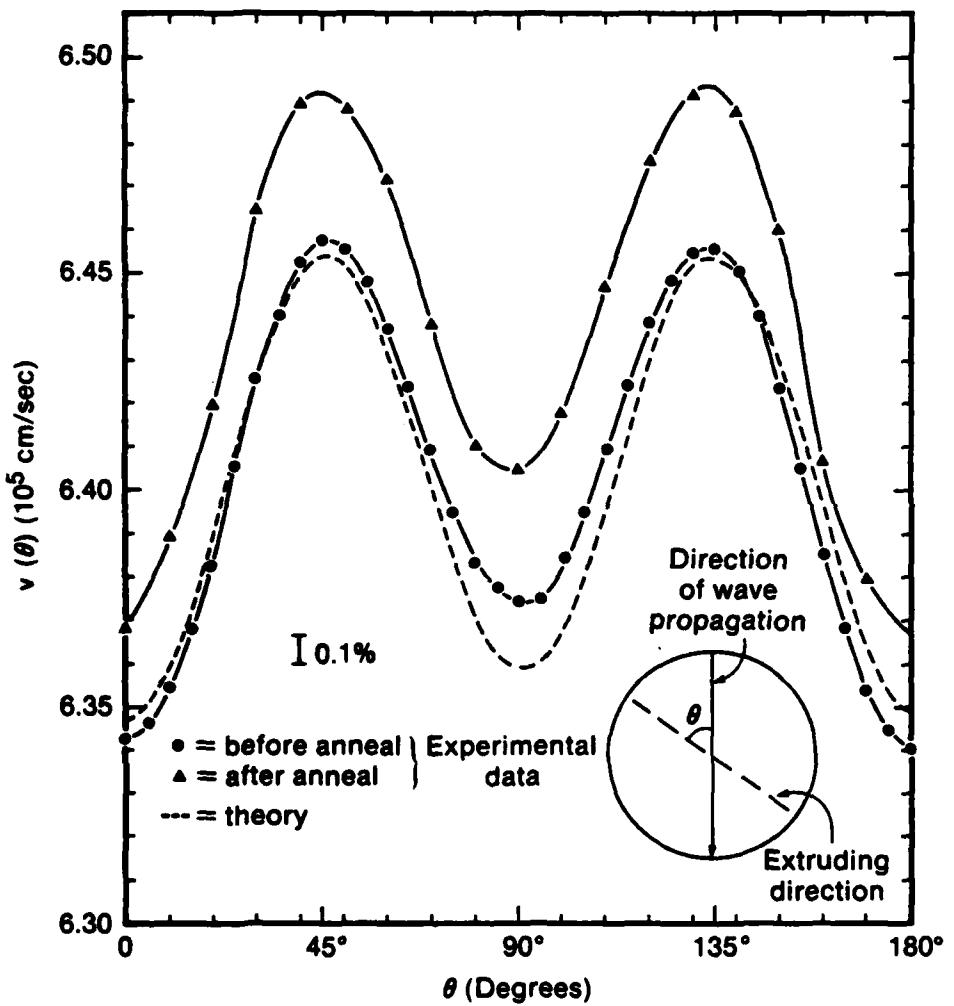


Figure 3. Longitudinal ultrasonic wave velocity $v(\theta)$ in extruded aluminum alloy (6061-T6) as a function of θ , the angle between the direction of extrusion and that of propagation of ultrasonic waves. The solid lines are drawn through the experimental data points to guide the eye, while the dotted line is a theoretical curve based on a one-phase aggregate model for the metal.

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